HCPV Characterization: Analysis of Fielded System Data

Bruce King[1], Dan Riley[1], Clifford Hansen[1], Matt Erdman[1], John Gabriel[2] and Kanchan Ghosal[2]

[1]*Sandia National Laboratories, Albuquerque, NM 81785, USA*
[2]*Semprius, Inc., 4915 Prospectus Drive, Suite C, Durham, NC 27713, USA*

Abstract. Sandia and Semprius have partnered to evaluate the operational performance of a 3.5 kW (nominal) R&D system using 40 Semprius modules. Eight months of operational data has been collected and evaluated. Analysis includes determination of P_{mp}, I_{mp} and V_{mp} at CSTC conditions, P_{mp} as a function of DNI, effect of wind speed on module temperature and seasonal variations in performance. As expected, on-sun P_{mp} and I_{mp} of the installed system were found to be ~10% lower than the values determined from flash testing at CSTC, while V_{mp} was found to be nearly identical to the results of flash testing. The differences in the flash test and outdoor data are attributed to string mismatch, soiling, seasonal variation in solar spectrum, discrepancy in the cell temperature model, and uncertainty in the power and current reported by the inverter.. An apparent limitation to the degree of module cooling that can be expected from wind speed was observed. The system was observed to display seasonal variation in performance, likely due to seasonal variation in spectrum.

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INTRODUCTION

The Photovoltaic Systems Evaluation Lab (PSEL) at Sandia National Laboratories has a long history of characterizing photovoltaic modules of different technologies, including silicon, thin film and CPV. This module-level characterization activity has gradually expanded over the last 10 years to include the long-term analysis of small systems (1-5 kW), however the focus has been exclusively on flat-plate PV technologies [1, 2]. Recently, Sandia and Semprius partnered to install a 3.5 kW R&D CPV system in Albuquerque.

SYSTEM DESCRIPTION AND INSTRUMENTATION

A 3.5 kW R&D system consisting of 40 Semprius pre-production modules was installed at Sandia in July 2013 (Figure 1). These modules have an optical concentration ratio of 1111X and an average efficiency of 32.6% at CSTC conditions [3]. The system uses a Feina SF45 two-axis tracker+ and a grid-tied Kaco* 3502xi inverter. Instruments mounted directly on the tracker measure GNI and DNI while a nearby metrology package monitors precipitation, ambient temperature, wind speed and GHI. System DC and AC voltage, current and power, as reported by the Kaco inverter, are logged on a 1-minute interval via a Campbell Scientific CR-1000. The system has recently been upgraded to include independent electrical measurements via voltage transducers and current shunts, however insufficient data has been collected to date to include here. Sandia maintains an independent, comprehensive weather station in close proximity to the Semprius system that monitors DNI, GNI and global normal spectrum, among other relevant measurements.

FIGURE 1. 3.5 kW R&D System installed at Sandia

+ Trackers Feina S.L., Barcelona, Spain
* KACO new energy GmbH, Neckarsulm, Germany

PEFORMANCE OBSERVATIONS

Full system commissioning was completed in July of 2013 and the data collection period presented here was August 2013 to March 2014. AC measurements were available but this data was only used for filtering. All results presented in this paper are for DC measurements only.

Data Filtering and Analysis

Prior to analysis, it was necessary to filter the data to remove extraneous points. The general filtering conditions are shown in Table 1. Further data binning was performed as needed for the individual analyses.

TABLE 1. General Data Filtering Conditions. Data records not meeting the following criteria were excluded.

DNI, W/m^2	> 50
AC Power, W	>150
DC Voltage, V	415 – 465
AC/DC Ratio	< 1.0
DNI/GNI	0.04 – 0.95

Performance at Reference Conditions

The full eight months of data collected on the operational system was analyzed to determine power at CSTC rating conditions [4]. The filtered system data was further binned to conditions bracketing the reference conditions (Table 2). It was possible to maintain tight binning criteria for DNI due to typical conditions at the test site. Power, current and voltage were corrected for temperature [5] using temperature coefficients determined for a similar R&D module characterized separately at Sandia. Temperature corrected P_{mp}, I_{mp} and V_{mp} from this subset were plotted against DNI over this narrow band and reference conditions were determined by regression analysis.

TABLE 2. Binning Criteria for CSTC Determination.

DNI, W/m^2	990 - 1010
DNI/GNI	> 0.85
Spectrum, AM	1.45 – 1.55
Wind Speed, m/s	< 2.5
# of Data Points	1084

The results of this analysis are shown in Table 3 along with the nameplate values and flash test data at CSTC. Outdoor P_{mp} and I_{mp} were observed to be about 10% lower than the flash test data, while V_{mp} was essentially the same. This observation is in line with expectations. Mismatch loss were expected to be 3% or greater based on flash test results and the configuration of the modules in a string. Daily and seasonal variations in spectrum were expected to result in an underestimation of 3-5%. Discrepancy in the cell temperature model and uncertainty in the power and current reported by the inverter may have also contributed to this difference.

TABLE 3. P_{mp}, I_{mp} and V_{mp} at CSTC

Condition	P_{mp}, W	I_{mp}, A	V_{mp}, V
Nameplate	3500	8.08	433
Flash	3503	7.624	459
Outdoor	3128	6.829	461

Annual System Performance

The full eight months of data was analyzed to identify annual performance trends. The CSTC values determined from the outdoor system were used to normalize performance parameters in these analyses.

DC Power vs. Irradiance

Temperature corrected P_{mp} was normalized by $P_{mp,CSTC}$ and plotted against DNI (Figure 2). An additional filter was applied that removed data for wind speeds greater than 5 m/s, but the data are not filtered to exclude transitory or partial shading. This data was not adjusted to account for variation in spectrum and the temperature correction procedure employs a relatively simple model. As a result, the data appears as a wide band along a linear trend, as would be expected, but with scattered points at lower P_{mp} indicative of partial shading. The vast majority of data points are clustered at higher DNI values, above 0.6, a consequence of the typical environmental conditions at Sandia's test site.

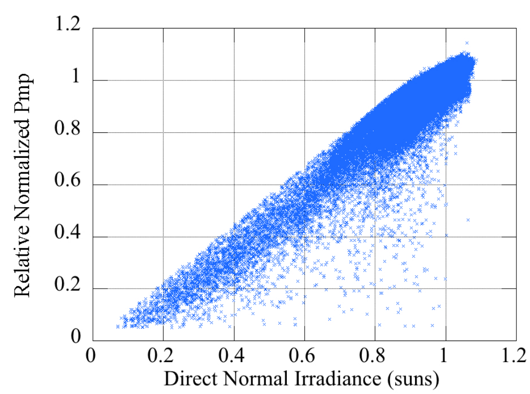

FIGURE 2. Relative Normalized P_{mp} vs DNI.

Wind Speed

The effect of wind speed on module temperature was explored following the methodology in Reference

4. The natural log of the measured temperature difference between the back surface of the module and ambient divided by DNI is plotted against average wind speed in Figure 3. The data suggests that there is a threshold at y=-4.5, which corresponds to a temperature difference of 11°C at 1000 W/m^2. The implication is that above a certain wind speed, between 5 and 6 m/s, the modules reach a steady state condition where further increases in wind speed do not result in greater cooling.

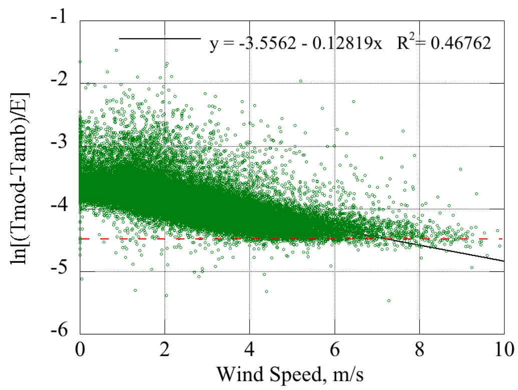

FIGURE 3. Effect of Wind Speed on Module Temperature. An apparent threshold beyond which further increases in wind speed do not result in greater cooling is shown by the broken red line.

Seasonal System Performance

To examine seasonal variations in performance, one clear day from each month of operation was selected for analysis. Candidate clear days were defined by visually inspecting monthly calendar plots of DNI vs. Time of Day. These days were then screened for system outages and DNI/GNI > 0.85. The specific days selected are listed in Table 4.

Monthly Variation in Energy Yield

Performance Ratio, commonly used to rate monthly or yearly performance in a normalized, dimensionless fashion [6, 7] is also a useful metric for comparing performance over shorter time periods. DC Performance Ratio (PR_{DC}) was calculated for each clear sky day selected to represent each month. These results are shown in Table 4 along with Net Energy (kWh) and average and peak DNI for each day.

There is a clear trend toward lower PR_{DC} during the winter months and higher PR_{DC} during summer months. Because the use of PR_{DC} as a performance metric removes the effect of the length of the day, it's tempting to assume that this is due to lower irradiance during the winter months. However, examination of average and peak irradiance values for each day revealed that both values were actually higher during the winter than during the summer. One possible explanation for the seasonal changes in PR_{DC} can be found by examining I_{mp} as a function of air mass.

TABLE 4. Seasonal Variation in Energy Production and Performance Ratio.

Date	DC Energy, kWh	PR_{DC}	DNI, W/m^2 Avg	DNI, W/m^2 Peak
16-Aug	8.258	0.95	899	980
23-Sept	8.600	0.93	955	1023
21-Oct	7.226	0.90	944	1010
9-Nov	6.984	0.90	972	1029
23-Dec	6.530	0.87	976	1036
21-Jan	6.848	0.86	925	1063
21-Feb	7.383	0.90	982	1036
16-Mar	9.443	0.89	1006	1076

DC Current vs Airmass

Because of its simplicity and ease of use, air mass (AMa) is frequently used in performance models as a proxy for spectrum [4]. A known limitation of air mass is that it does not represent the influence of variable atmospheric components such as water vapor on spectrum. The effect of varying spectrum on performance is typically represented by an air mass dependent factor applied to I_{sc}. Because this study was conducted on a system operated at maximum power, I_{sc} information was not available for analysis. Instead, the effect of AMa on I_{mp} was explored.

Three clear sky days were selected from those listed in Table 5. Days in September, December and March were chosen due to their proximity to the seasonal changes. Temperature and irradiance corrected I_{mp} was normalized by the CSTC reference value of 6.829A determined from outside testing and compared to AMa (Figure 4).

Several important features are worth noting. First, the Sun's zenith angle is lower in the winter than in the fall and spring, consequently the minimum AMa that can be achieved near the winter solstice is ~1.6, while at the equinoxes it is ~1.0. Secondly, I_{mp} displays a peak near AMa=2 during the equinoxes. This is consistent with I_{sc} measurements made on similar R&D modules characterized previously at Sandia under more controlled conditions. In contrast, at the winter solstice it is difficult to discern a peak due to the limited range of AMa that can be achieved.

Third, a clear splitting of I_{mp} behavior can be observed between morning (lower leg) and afternoon (upper leg). This has been observed at Sandia for other technologies and is thought to be the result of a difference in actual spectral conditions between morning and afternoon, which is not captured by AMa. In particular, it is suspected that the morning sky is red-shifted.

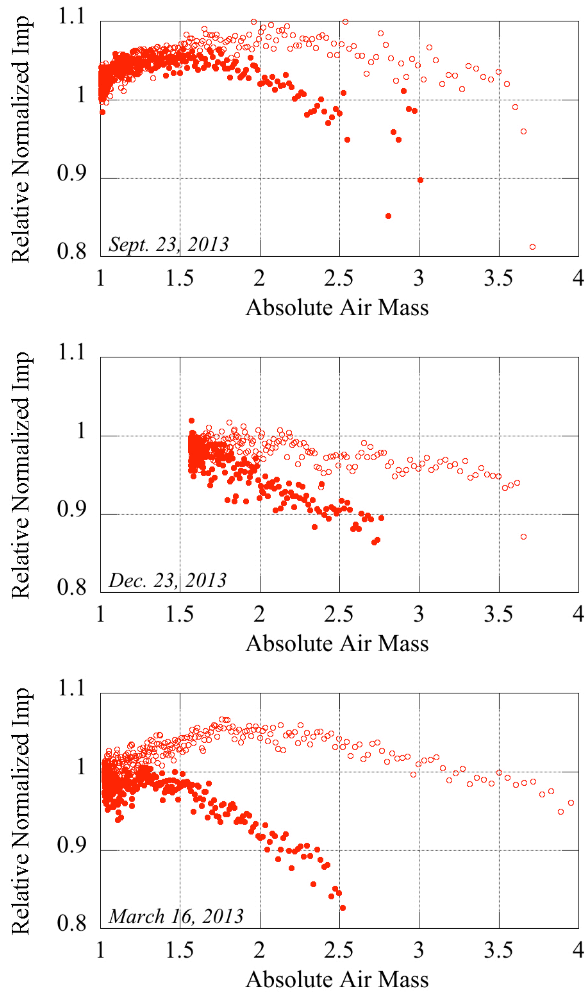

FIGURE 4. Relative Normalized Imp vs. Air Mass at the Equinoxes and winter Solstice. Closed circles represent morning and open circles represent afternoon.

Finally, it was observed that the relative normalized I_{mp} was consistently higher (> 1) at the equinoxes while at the solstice it was observed to have a maximum near unity. On average, it would appear that spectral conditions favor greater output from this particular technology during the summer and lower output during the winter. However, other explanations for the seasonal variation in PR_{DC} can be offered. For example, air temperature - and hence module temperature - generally increases from morning to afternoon, and thus a discrepancy in temperature corrections to Imp could also give rise to the patterns evident in Figure 4. Further analysis of a full year's worth of data in the summer of 2014 will help explain the variation in PR_{DC}.

CONCLUSIONS

Eight months of operational data from a 3.5 kW (nominal) HCPV R&D system was analyzed to determine P_{mp}, I_{mp} and V_{mp} at CSTC conditions. As expected, on-sun P_{mp} and I_{mp} of the installed system were found to be ~10% lower than the values determined from flash testing at CSTC, while V_{mp} was found to be nearly identical to the results of flash testing. The differences in the flash test and outdoor data are attributed to string mismatch, soiling, seasonal variation in solar spectrum, discrepancy in the cell temperature model, and uncertainty in the power and current reported by the inverter. An apparent limitation to the degree of module cooling that can be expected from wind speed was observed. The system was observed to display variation in seasonal performance ratio, likely due to seasonal variation in spectrum.

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